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A Rehabilitation Walker with a Standing Assistance Device

Daisuke Chugo* and Kunikatsu Takase**
**Kwansei Gakuin University*
Hyogo, Japan
***The University of Electro-Communications*
Tokyo, Japan

1. Introduction

In Japan, the population ratio of senior citizen who is 65 years old or more exceeds 22[%] at January 2009 and rapid aging in Japanese society will advance in the future (Population Estimates, 2009). In aging society, many elderly people cannot perform normal daily household, work related and recreational activities because of decrease in force generating capacity of their body. Today, the 23.5[%] of elderly person who does not stay at the hospital cannot perform normal daily life without nursing by other people (Annual Reports, 2001). For their independent life, they need domestic assistance system which enable them to perform daily life easily even if their physical strength reduces.

Standing up motion is the most serious and important operation in daily life for elderly person who doesn't have enough physical strength (Alexander et al., 1991) (Hughes & Schenkman, 1996). In typical bad case, elderly person who doesn't have enough physical strength will cannot operate standing up motion and will falls into the wheelchair life or bedridden life. Furthermore, if once elderly person falls into such life, the decrease of physical strength will be promoted because he will not use his own physical strength (Hirvensalo et al., 2000). Therefore, we are developing the force assistance system for standing up motion which uses part of the remaining strength of the patient in order not to reduce their muscular strength.

In previous works, many researchers developed power assistance devices for standing up motion. However, these devices are large scale and they are not suitable for family use (Nagai et al., 2003) (Funakubo et al., 2001) (Chuv et al., 2006). Furthermore, these devices assist all necessary power for standing up and they do not discuss about using remaining physical strength of patients. Therefore, there is still a risk of promoting the decrease of their physical strength.

In this paper, we develop a walker system with power assistance device for standing up motion. Our system is based on a walker which is popular assistance device for aged person in normal daily life and realizes the standing up motion using the support pad which is actuated by the manipulator with three degrees of freedom. For using the remaining

physical strength, our system uses the motion pattern which is based on the typical standing up motion by nursing specialist as control reference (Chugo et al., 2006).
Our key ideas are two topics. The first is new assistance manipulator mechanism with four parallel linkages which enables the system to be rigid and compact. The second is the combination of force and position control. Using our control scheme, the patients can stand up with fewer loads and can use their own remaining physical strength during the motion. We verify the performance of our proposed assistance system through simulations and experiments using our prototype.
This paper is organized as follows: we introduce the mechanical design and derive its inverse kinematics of our assistance system in section 2; we analyze the standing up motion by nursing specialist in section 3; we propose the new control scheme and show the result of computer simulations and experiments using our prototype in section 4; section 5 is conclusion of this paper.

2. System Configuration

2.1 Assistive Mechanism

Fig.1 and Fig.2 show our proposed assistance system. The system consists of a support pad with three degrees of freedom and the walker system. The support pad is actuated by our new assistance manipulator mechanism with four parallel linkages. Our prototype can lift up the patient of 180[cm] height and 150[kg] weight maximum.

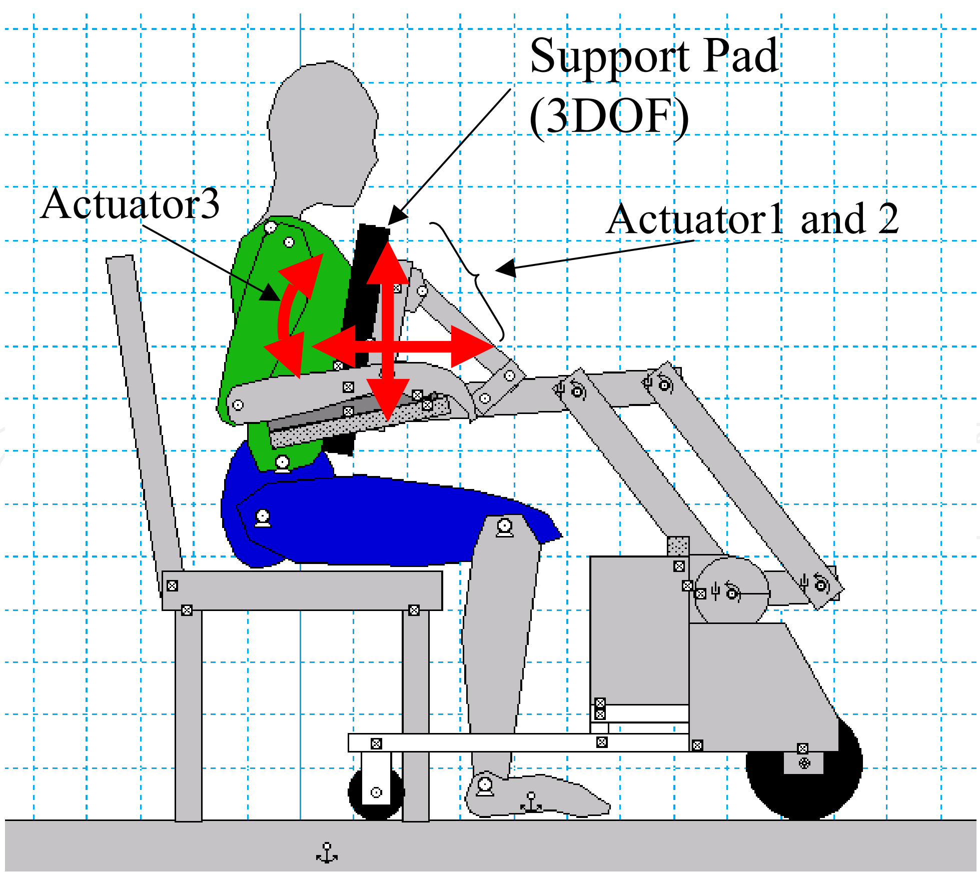


Fig. 1. Overview of our system.

(a) Side view (b) Front View

Fig. 2. Our prototype. Its weight is about 35[kg] without batteries. Our prototype requires an external power supply and control PC. (In future works, we will use batteries and built-in controller.)

Our assistance system assumes the patient leans on the support pad during the standing assistance. We demonstrated our prototype standing assistance system in a welfare event (Chugo & Takase, 2008) and we asked patients, nursing specialists and physical therapist for advice. They indicated the following points.

- Patient's arm should be on the arm holder.
- Handles are required because it helps aged person to fix their arm on the arm holder with his weak grip.
- The support pad should hold the patient body without a slip down to sideways.
- The support pad should hold the patient softly because strong pressure causes obstruction of blood circulation.

Considering with these opinions, we design the support pad as shown in Fig.3(a). The support pad consists of the pad with low repulsion cushion and arm holders with handles. Both sides of this cushion are thick and it holds the patient body without slipping down. The patient leans on the pad, puts the arm holder and grasp the handle during standing up with our assistance system as Fig.3(b). The assistance posture of the patient is based on the assistance scheme of nursing specialist (Kamiya, 2005). (We discuss in section next section.)
In general, a fear of falling forward during standing motion reduces the standing ability of elderly person (Maki et al., 1991). Using this pad, a patient can maintain his posture easily during standing up motion without a fear of falling forward. Furthermore, the pad has force

sensors in its body. Our assistance system can measure its applied force and can estimate a body balance of the patient during standing up motion using these sensors.

(a) Support Pad (b) Assistance Posture

Fig. 3. Our proposed support pad. (1) is the pad with a low repulsion cushion, (2) is the arm holder and (3) is a handle. Its diameter is 0.24[m] which is easy to grip for the elderly. Our support pad has force sensors in its body.

Fig.4 shows the frame-kinematic model of our assistance manipulator. The position of the support pad (2DOF) is coordinated by Actuator 1 and Actuator 2 which are equipped on O point. Actuator 1 drives Link1 (α) and Actuator 2 drives Link2 (β). Using four parallel linkages mechanism, two actuators can generate the position of the support pad. The inclination of the support pad (1DOF, θ_3) is coordinated by Actuator 3 which is equipped on P point.

The advantages of our proposed mechanism are two topics. The first is that two main actuators (Actuator 1 and 2) are required to keep only weight of linkages. In general manipulator, the actuator of lower part supports not only weight of linkages but also actuators of upper part. Therefore, the actuators of lower part are required high output traction and tend to be heavy. On the other hand, using our mechanism, main actuators are mounted on the walker body (O point) and they are required to keep only weight of linkages. As the result, we can use smaller actuators for our assistance manipulator.

The second is that the parallel linkage mechanism is strong for a twist load. Using the parallel linkage mechanism, our actuator system can realize same strength with lighter linkages comparing with the general one. Using our proposed mechanism, we can use smaller actuators and lighter linkages, and our system realizes compact design with low cost.

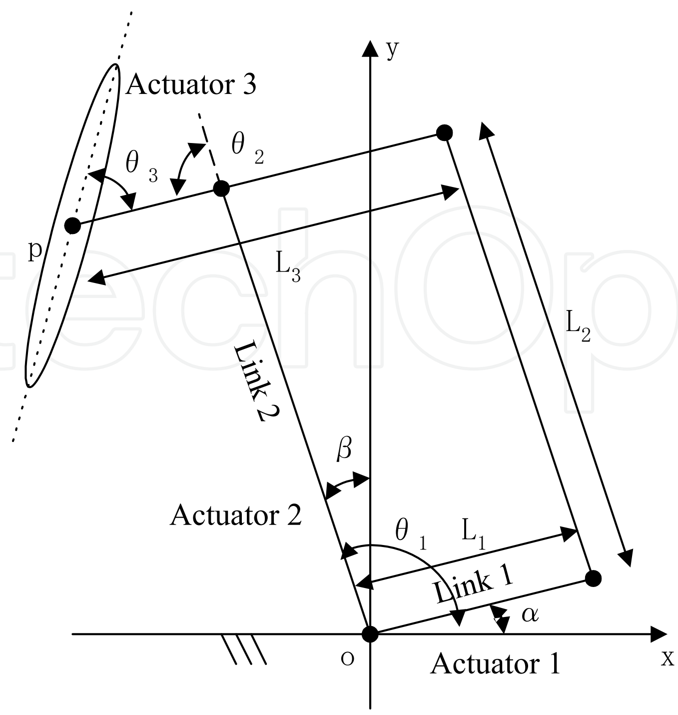


Fig. 4. The flame-kinematic model of developed system.

3.2 Kinematics

In this section, we derive the inverse kinematics of our proposed linkage mechanism. Using our proposed mechanism, the position of P point (We define its coordinates as (x_p, y_p)) is derived as follows;
The first, we set angular values and length of linkages as in Fig.4.

$$\theta_1 = \frac{\pi}{2} + \beta \,,\; \theta_2 = \frac{\pi}{2} + \alpha - \beta \tag{1}$$

$$l_1 = L_2 \,,\; l_2 = L_3 - L_1 \tag{2}$$

where α and β are angular value of Actuator 1 and Actuator 2, respectively. L_1, L_2 and L_3 are length of linkages.
Now, we consider the geometric relationships among the position of P point and these angular values, we can derive (3) and (4).

$$x_p = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \tag{3}$$

$$y_p = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \tag{4}$$

From (3) and (4), θ_2 is (5).

$$\theta_2 = \arccos\left(\frac{x_p^2 + y_p^2 - l_1^2 - l_2^2}{2l_1 l_2}\right) \tag{5}$$

We set k_1 and k_2 as (6), (3) and (4) are expressed as (7) and (8).

$$k_1 = l_1 + l_2 \cos\theta_2,\ k_2 = l_2 \sin\theta_2 \tag{6}$$

$$x_p = k_1 \cos\theta_1 - k_2 \sin\theta_1 \tag{7}$$

$$y_p = k_1 \sin\theta_1 + k_2 \cos\theta_1 \tag{8}$$

Furthermore, we set r and γ as (9), k_1 and k_2 are expressed as (10).

$$r = \sqrt{x_p^2 + y_p^2},\ \tan\gamma = \frac{k_2}{k_1} \tag{9}$$

$$k_1 = r\cos\gamma,\ k_2 = r\sin\gamma \tag{10}$$

Using (10), (7) and (8) are expressed as (11) and (12).

$$x_p = r\cos(\gamma + \theta_1) \tag{11}$$

$$y_p = r\sin(\gamma + \theta_1) \tag{12}$$

From (11) and (12), we can derive (13).

$$\tan(\gamma + \theta_1) = \frac{y_p}{x_p} \tag{13}$$

Thus, θ_1 is (14).

$$\theta_1 = \arctan\left(\frac{y_p}{x_p}\right) - \arctan\left(\frac{l_2 \sin\theta_2}{l_1 + l_2 \cos\theta_2}\right) \tag{14}$$

Using (5) and (14), we can control our manipulator. The lengths of its linkages are L_1 =150[mm], L_2 =450[mm], L_3 =480[mm], and the movable range of the support pad is 520[mm] in horizontal direction (X-axis) and 580[mm] in vertical direction (Y-axis). This range is enough for assisting the standing up motion for the 180[cm] height patient.

3. Standing up Motion

3.1 Motion by Nursing Specialists

In previous study, a lot of standing up motions for assistance are proposed. Kamiya (Kamiya, 2005) proposed the standing up motion which uses remaining physical strength of the patients maximum based on her experience as nursing specialist. Fig.5 shows the standing up motion which Kamiya proposes.

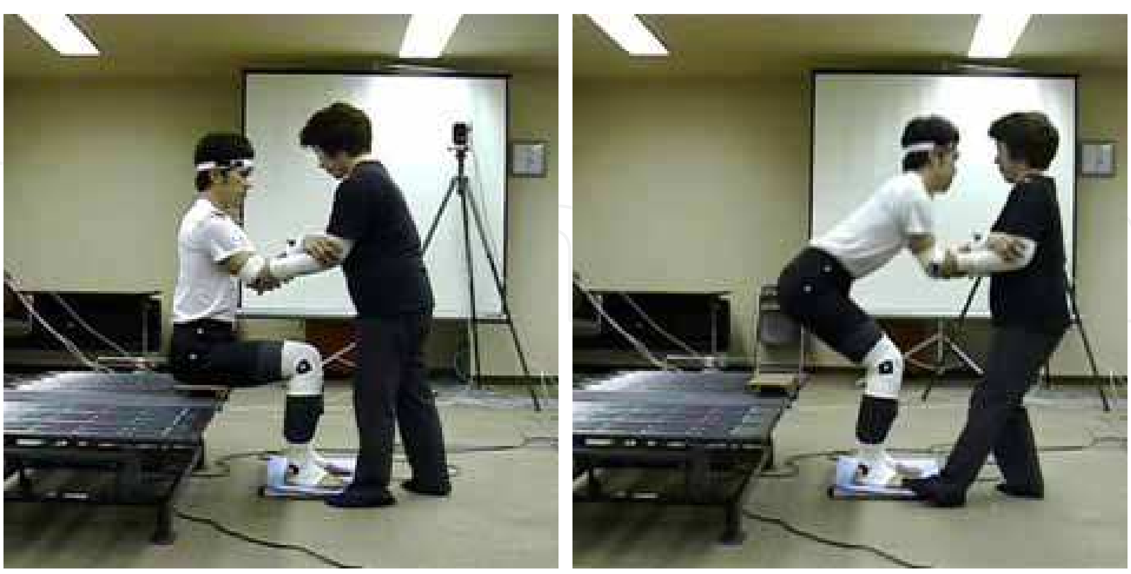
In our previous work, we analyze this standing up motion and find that Kamiya scheme is effective to enable standing up motion with smaller load (Chugo et al., 2006). We assume the standing up motion is symmetrical and we discuss the motion as movement of the linkages model on 2D plane (Nuzik et al., 1986). We measure the angular values among the linkages, which reflect the relationship of body segments. The angular value is derived using the body landmark as shown in Fig.6 (a).

In order to realize the Kamiya scheme, the trunk needs to incline to forward direction during lifting up from chair as shown in Fig.6 (b). Y-axis shows the angular value (Pelvis /trunk, knee, ankle) and X-axis shows the movement pattern (Hughes & Schenkman, 1996) which means the ratio of standing up operation as (15).

$$\hat{s} = \frac{t}{t_s} \tag{15}$$

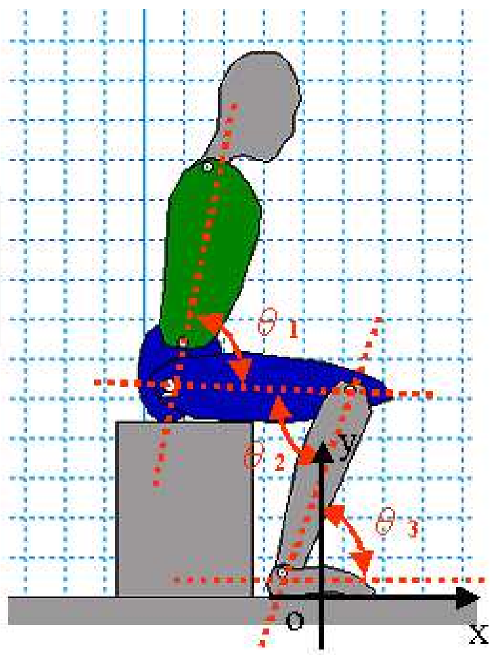
where t_s is required time to the standing up operation and t is present time.

Generally, inclining the trunk reduces the load of knee during standing up (Fisher et al., 1990) and this motion is useful for elderly person who doesn't have enough physical strength. Therefore, in next section, we derived the control reference for our assistance system which realizes this motion using computer simulations.

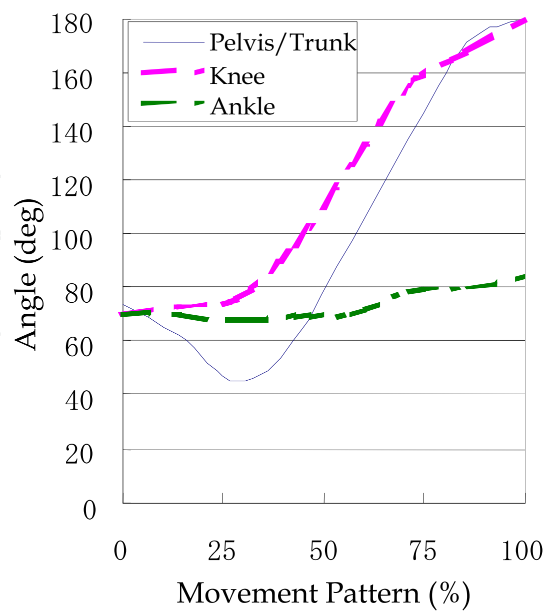


(a) (b)

Fig. 5. Standing-up motion with Kamiya scheme



(a) Coordination



(b) Angular Value

Fig. 6. Standing-up motion with Kamiya scheme. θ_1 shows the angular of the pelvis and the trunk. θ_2 and θ_3 shows the angular of the knee and the ankle, respectively.

3.2 Derivation of Control Reference

In this section, we derive the control reference of our assistance system which can realize the standing up motion proposed by Kamiya using a computer simulation. Fig.7 shows the simulation setup. The parameters are chosen from a standard body data of adult male (Digital Human) (Okada et al., 1996) as shown in Table 1.

In derivation of the references using the simulation, we assume the following points.

- The human model moves each joints as Fig.6(b).
- The human model puts his forearm on the supporter.
- The human model leans on the pad using his arm with own enough force.
- We assume the height of human model is 170[cm].

Number	Link Name	Mass [kg]	Length [m]	Width [m]
1	Head	5.9	0.28	0.21
2	Trunk	27.2	0.48	0.23
3	Hip	18.1	0.23	0.23
4	Humerus	4.5	0.39	0.12
5	Arm	2.7	0.35	0.08
6	Hand	0.5	0.2	0.07
7	Femur	9.1	0.61	0.17
8	Leg	4.5	0.56	0.16
9	Foot	0.8	0.26	0.11

Table 1. Human Parameters

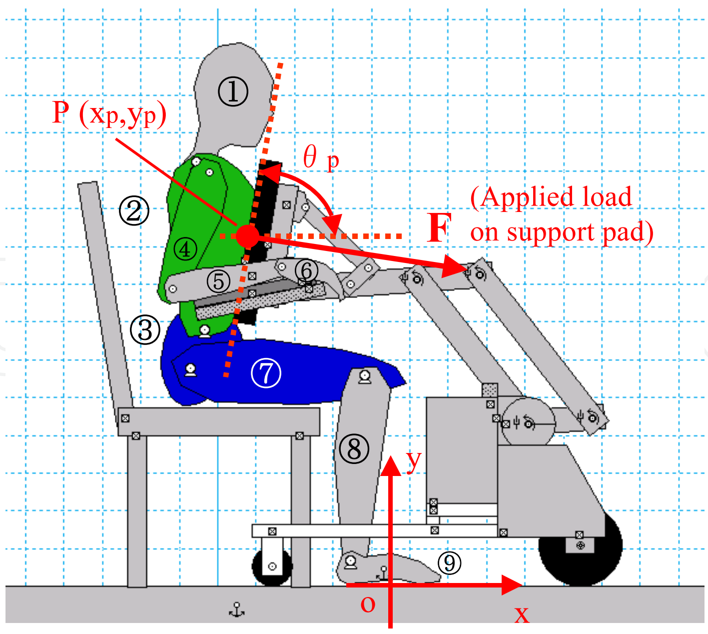
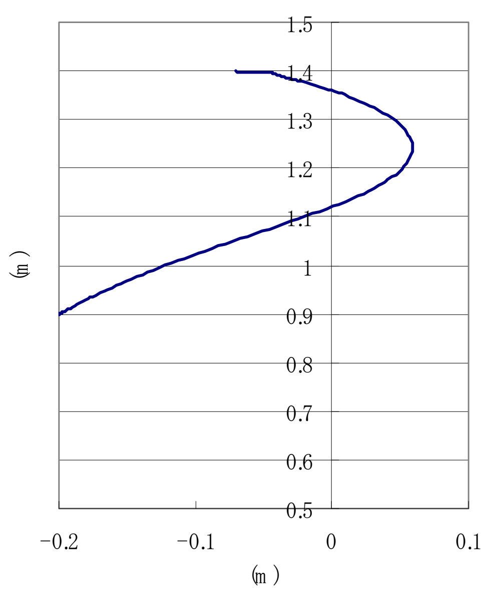
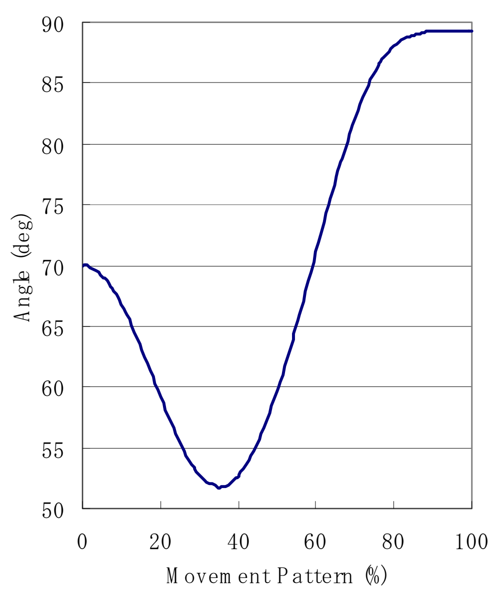


Fig. 7. Simulation setup.

We use the Working Model 2D as a physical simulator and MATLAB as a controller. Both applications are linked by Dynamic Data Exchange function on Windows OS.
From the simulation results, Fig.8(a) shows the position tracks of support pad and Fig.8(b) shows its angle tracks. In Fig.8(b), Y-axis shows the inclination angle of the support pad and X-axis shows the movement pattern $\hat{s}$. The coordination of Fig.8(a) and (b) is defined as shown in Fig.7. In Fig.8(a), the start point is lower left and the end point is upper center. Using these tracks as the position control reference, our assistance system can realize the standing up motion which Kamiya proposes.



(a) Position



(b) Inclination

Fig. 8. Derived control references.

Furthermore, we show the knee load of the patient and applied load on support pad during standing up in Fig.9. The knee load is larger than 0.5[Nm/kg]. In general, if the applied load to each joint is heavier than 0.5[Nm/kg], it is difficult to stand up for the elderly person (Omori et al., 2001). Therefore, it is required to reduce knee load during this standing-up motion.

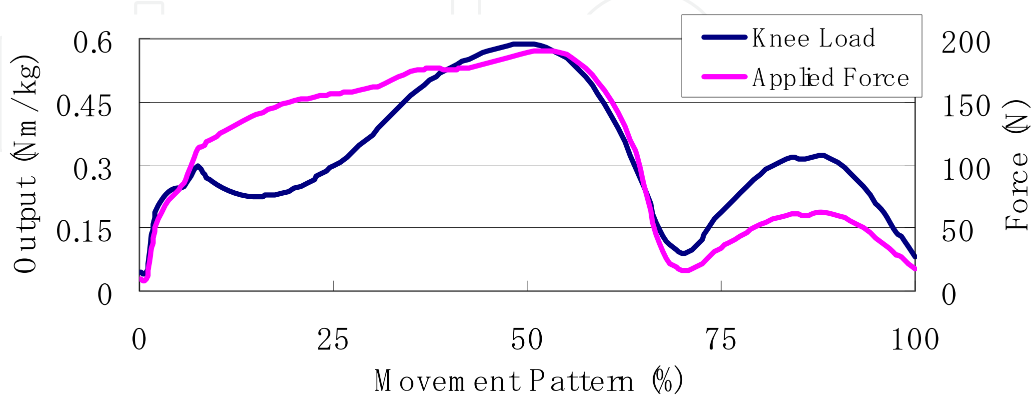


Fig. 9. Applied load on the pad and load of knee joint during human model stands up.

4. Force Control

4.1 Proposed Control Scheme

In general, we can divide the standing up motion into four phases (Schenkman et al., 1990). In first phase, the patient still sits and inclines his trunk to forward direction. In second phase, he lifts off from the chair and in third phase, he lifts the body. In fourth phase, he extends his knee joint completely and ends the standing up motion. From previous research, in third phase, it is required to force assistance because the knee load is heavy. On the other hand, in other phases, it is required to maintain the motion of Kamiya scheme.

Therefore, we propose new control scheme as shown in Fig.10. Proposed control scheme combines dumping control and position control. The dumping control is suitable for the control of the objects with contact (Sugihara et al., 2004). When the required torque of each joint is small enough in first, second and fourth phase, the controller uses the position control. On the other hand, when required torque of knee joint is heavy in third phase, the controller uses the dumping control.

We use the force sensor attached on the support pad for switching condition between the position control and the dumping control. Comparing with the knee load and applied force in Fig.9, the applied force to the support pad shows the same tendency to the applied load of knee joint. Therefore, we can divide the third phase and the other phases using the measuring value of the force sensor as a threshold. Using our proposed control scheme, the controller can select more appropriate control method using the force sensor on the support pad.

Now, we explain our proposed control scheme closely. The reference generator derives the velocity control reference of each actuator from motion reference by Kamiya as Fig.8.

$$\mathbf{v}_i^{ref} = \left[v_i^{ref}(0), \cdots, v_i^{ref}(\hat{s}), \cdots, v_i^{ref}(1)\right]^T \quad (16)$$

where v_i^{ref} is control reference and it is function of the movement pattern $\hat{s}$ as (15).
The output of each actuator is derived from (17).

$$v_i = v_i^{ref} - B(F - F_0) - K(x_i - x_i^{ref}) \tag{17}$$

where F is the applied force on the support pad and F_0 is the threshold which selects force or position control. v_i^{ref} is the velocity reference and x_i^{ref} is the position reference derived from track references as shown in Fig.8. v_i is the updated reference which our system uses actually during the assistance motion. B and K are constants.
When F is smaller than the threshold force F_0, the system sets $B = 0$ and selects position control mode. On the other hand, F is larger than the threshold force F_0, the system selects force control mode.

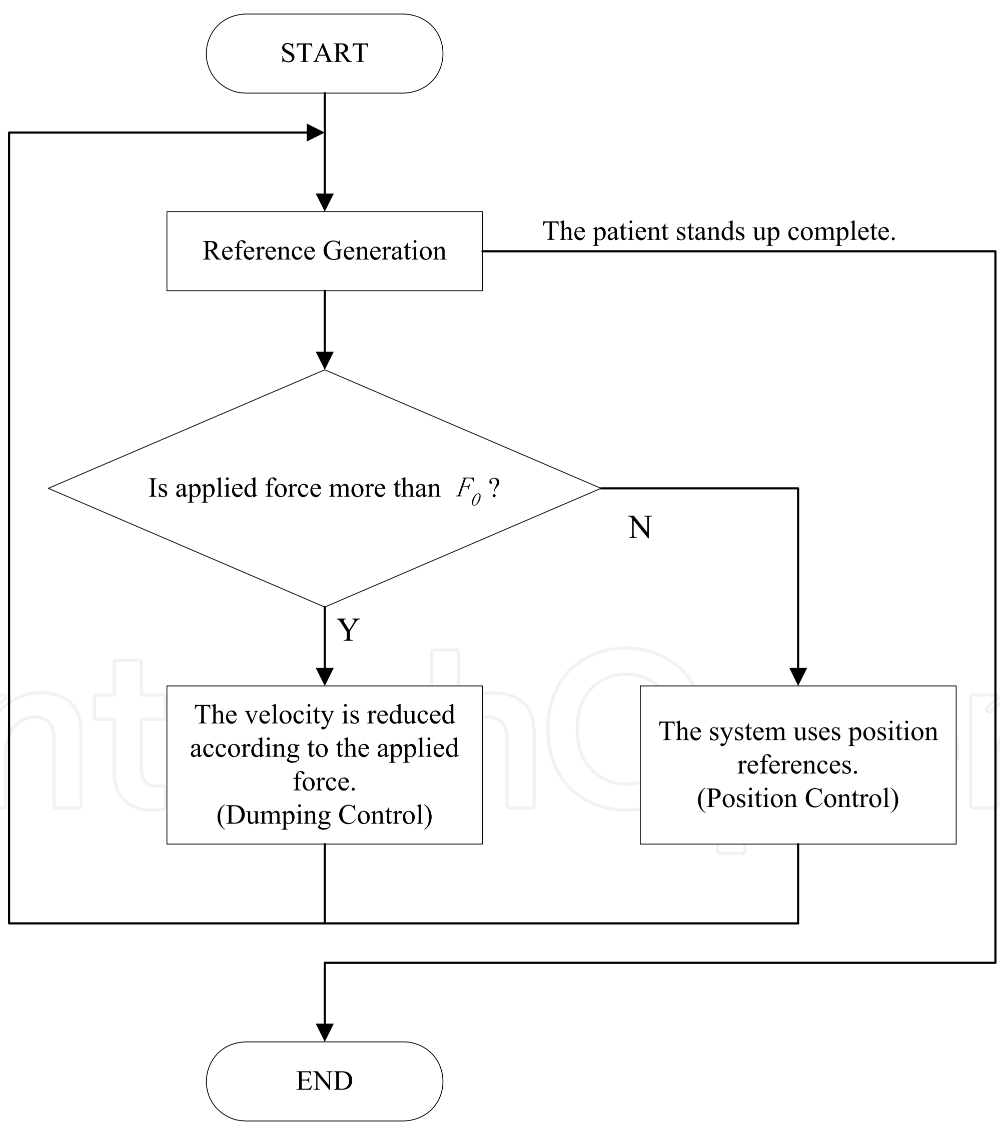


Fig. 10. Flow chart of our proposed control scheme.

4.2 Computer Simulation

We verify the performance of our control scheme by the computer simulation. In this experiment, the human model stands up with Kamiya motion as shown in Fig.6(b). For verifying the performance of our proposed control scheme, we experiment the following mode.

- Position control mode: The system uses only position control. ($B = 0, K = 0.2$)
- Proposed assistance 1: The system uses our proposed control scheme. (Position control mode: $B = 0, K = 0.2$, Force control mode: $B = 0.2, K = 0$)
- Proposed assistance 2: The system uses our proposed control scheme. In this mode, we set strong force control than in case of proposed assistance 1. (Position control mode: $B = 0, K = 0.2$, Force control mode: $B = 0.35, K = 0$)
- Force control mode: The system uses only force control mode. ($B = 0.35, K = 0$)

We use the control references as shown in Fig.8 which is derived from standing up motion with Kamiya scheme in previous section. The simulation parameters are chosen from Table 1. The coordination is defined in Fig.7. To prevent changing the control mode too frequently, we set the threshold as Fig.11. These values are derived experimentally.

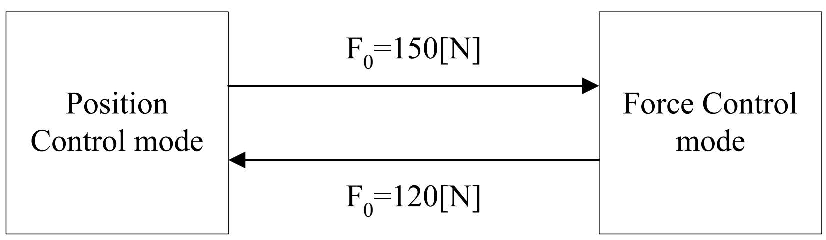


Fig. 11. Threshold.

Fig.12, Fig.13, Fig.14 and Table 2 show the simulation results. Fig.12 is standing up motion using our proposed assistance control. Allows in Fig.12 show the applied assistance force to the patient. The pad applies the force vertically to his body and the arm holder applies the force to his hand. Using our proposed control scheme, we verified that our assistance system realizes the natural standing up motion.

Fig.13 shows the applied force during standing up. During about 25 to 65[%] movement pattern, the force is larger than the threshold and force control mode is selected at our proposed assistance 1 and 2.

Fig.14 shows the output power of each joint. Force control reduces the output power of the patient comparing with the position control. From these results, we can verify that our proposed assistance uses force control mode during only 25 to 65[%] movement pattern (in third phase) and at other time, it uses position control. Our proposes assistance 2 is utilized stronger force control than in case of assistance 1, therefore, the output power of the patient at assistance 2 is less than assistance 1. Using our proposed assistance, system reduces maximum output of the patient into about 0.5[Nm/kg].

On the other hand, Table 2 shows the required workload of the patient for standing up motion. From these results, using our proposed assistance 1, the patients are required about 92[%] workloads for standing up motion comparing with no force assistance. Using force control, the patient uses only 73.1[%] workloads for the standing up motion. Therefore, this means our assistance system can use more part of his remaining strength.

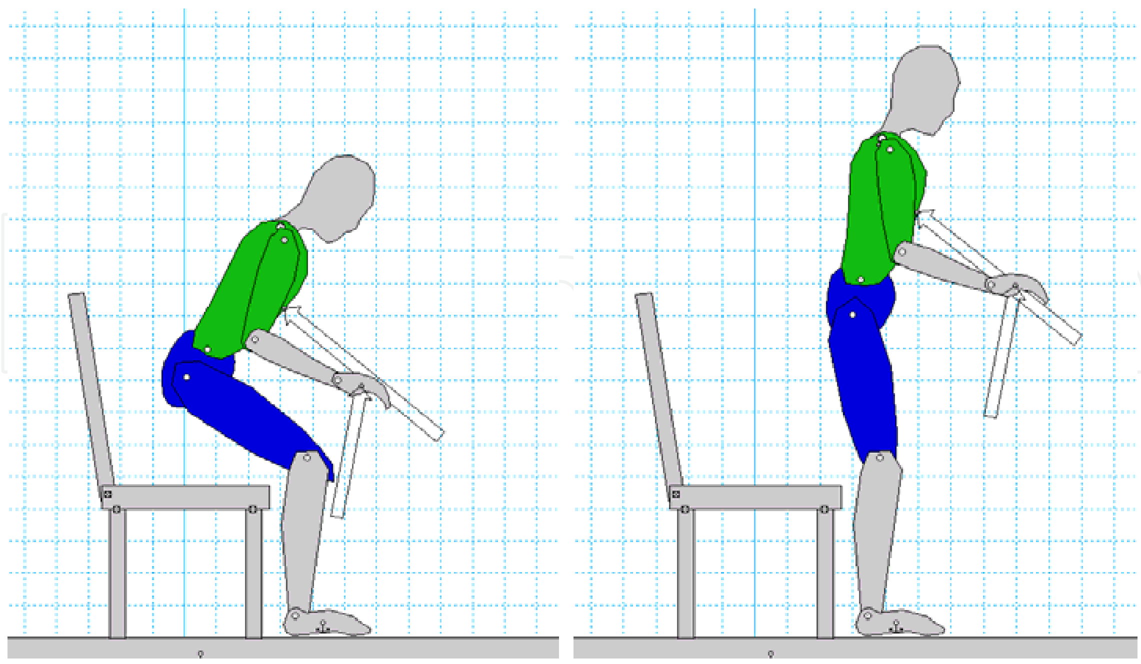


Fig. 12. Simulation result. Allows show the assistance forces. (Proposed assistance 1)

	Position	Assist1	Assist2	Force
Trunk	29.00	26.75 (92.2%)	24.74 (85.3%)	21.20 (73.1%)
Knee	39.28	35.27 (89.8%)	31.86 (81.1%)	28.70 (73.1%)
Ankle	30.90	28.84 (93.3%)	25.81 (83.5%)	22.60 (73.1%)
Total	99.18	90.86 (91.6%)	82.41 (83.1%)	72.50 (73.1%)

* Values in parentheses are the ratio comparing with the position mode.

Table 2. Workload for standing up. (Ws)

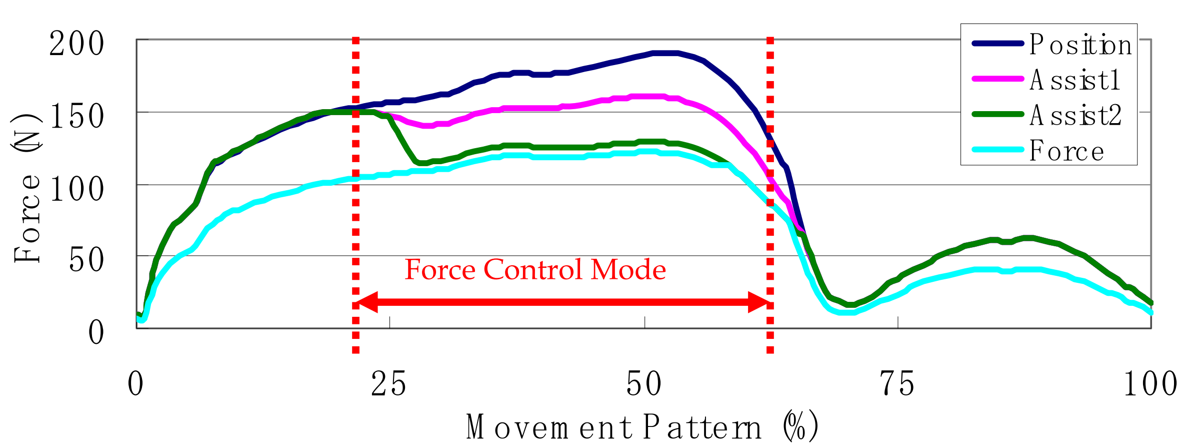
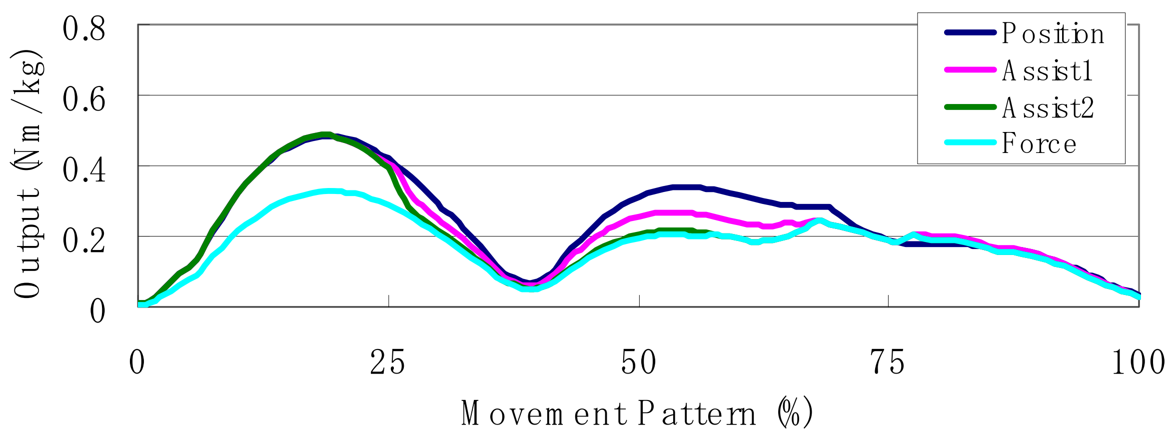
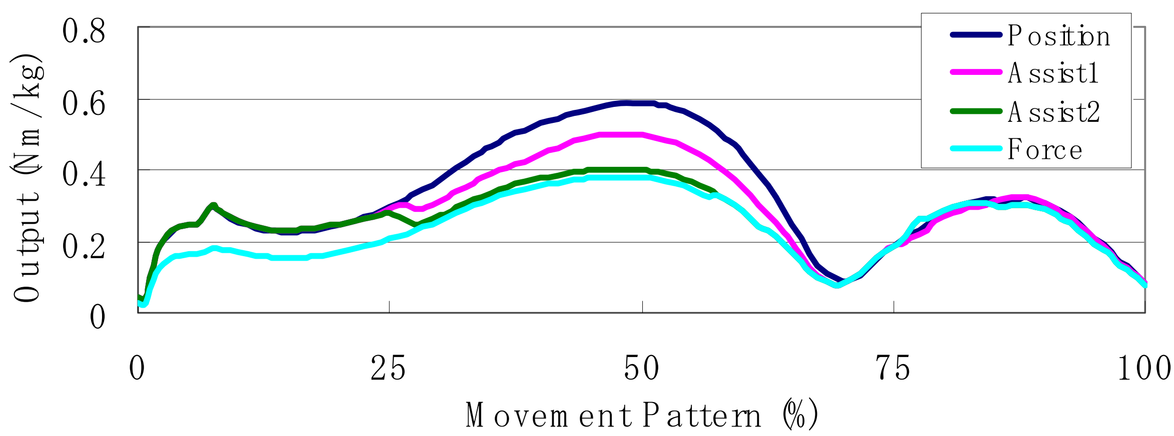


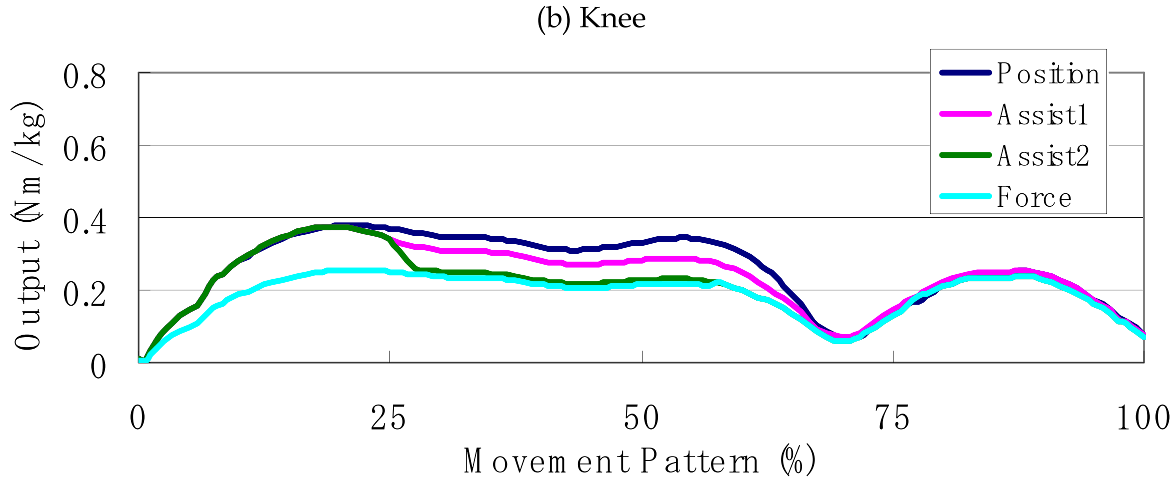
Fig. 13. Applied force.



(a) Trunk



(b) Knee



(c) Ankle

Fig. 14. Output force of each joint.

4.3 Experiments

Here, we verify the performance of our prototype system by the experiment. In this experiment, our prototype system assists the patient with our proposed control scheme. For verifying the performance of our proposed control scheme, we experiment the position mode ($B = 0$, always), our proposed mode (In position mode, $B = 0$. In force mode, $B = 0.3$.) and force control mode ($B = 0.3$, always). In order to verify the efficiency of force control clearly, the coefficient k is fixed to zero.

As the result of the experiment, our system can assist the patient as shown in Fig. 15. The height of the patient is 170[cm] and the system lifts him at 14[sec](Position control mode), 17[sec](Our proposed mode) and 23[sec](Force control mode). Our assistance system realizes the natural standing-up motion by nursing specialist.


(a)

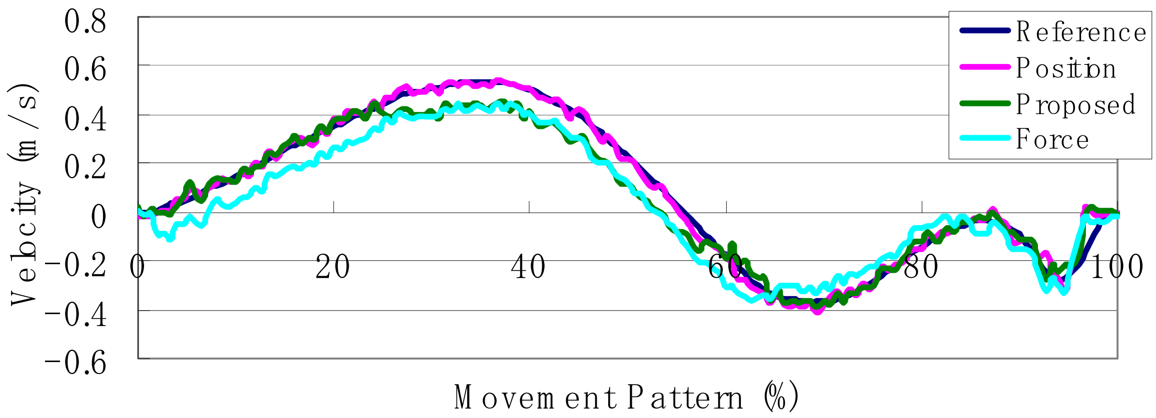

(b)


(c)

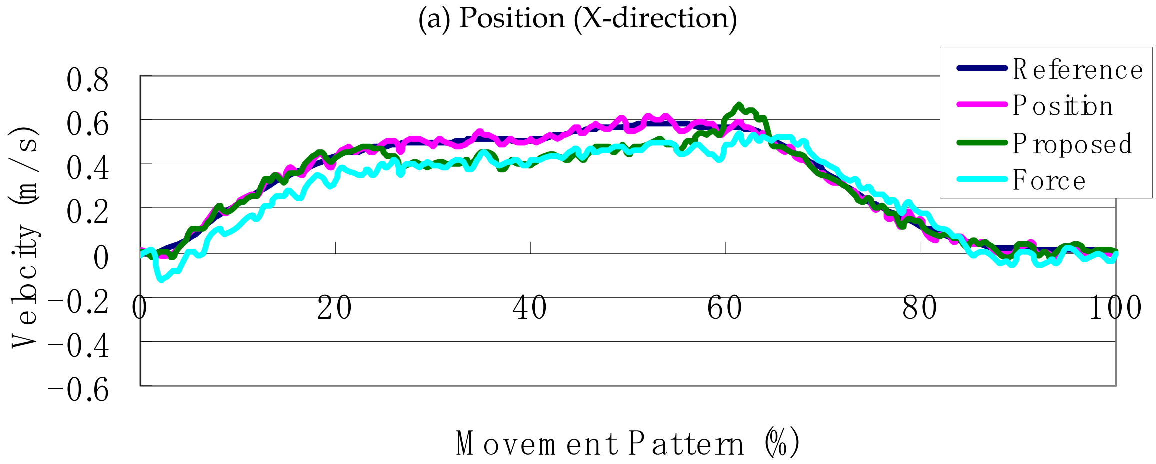

(d)

Fig. 15. Standing up motion with our system. (Our proposed scheme) The tester uses wearing equipment for the experience of the elderly (Takeda et al., 2001).

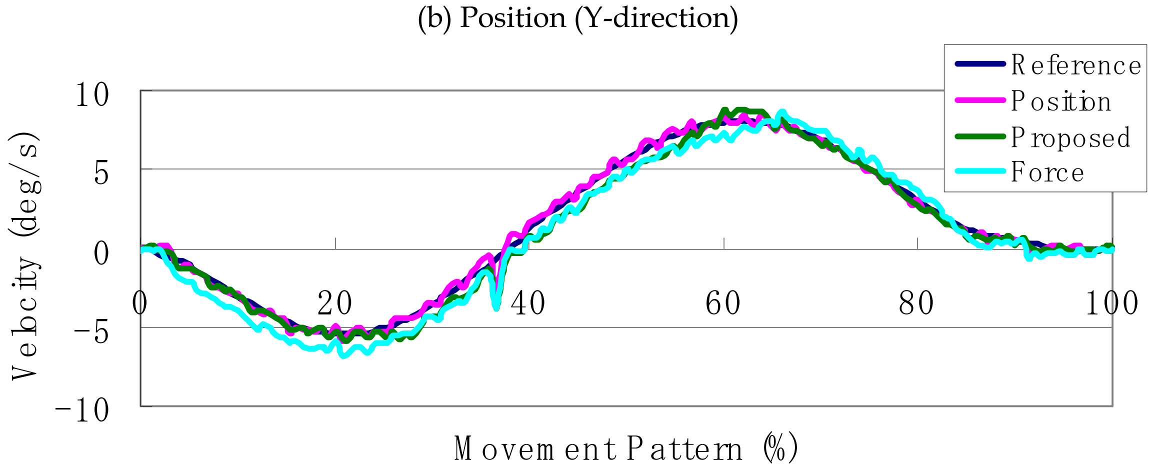
Fig. 16 shows the control reference and actually position and inclination of the support pad. Fig. 17 shows the applied force to the support pad. During 25 to 65[%] movement pattern (in third phase), system reduces the velocity of standing motion, therefore, the patient can use won physical strength easily and the applied force to the pad reduces. From these results, we can verify that force control mode works efficiency during 25 to 65[%] movement pattern (in third phase). Furthermore, we can verify that our proposed control scheme switches position control mode and force control mode during motion.



(a) Position (X-direction)



(b) Position (Y-direction)



(c) Inclination

Fig. 16. Experimental result.

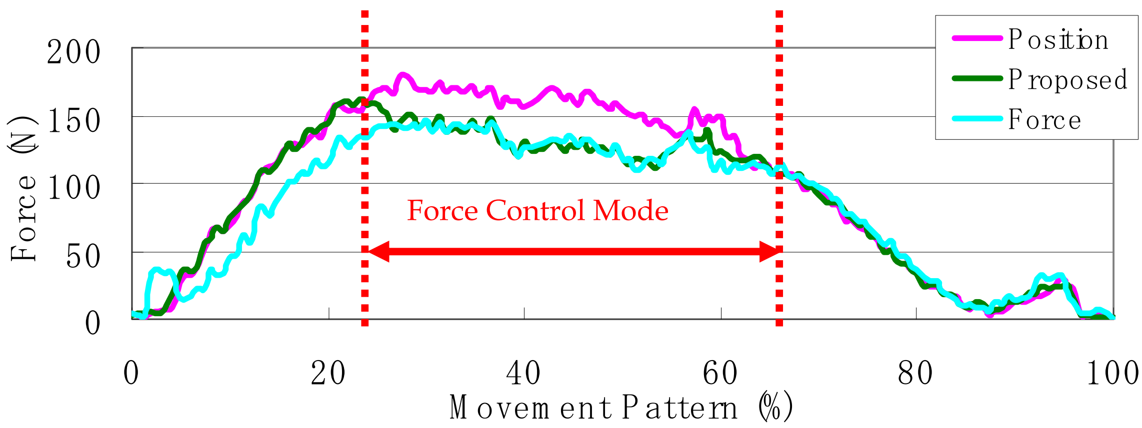
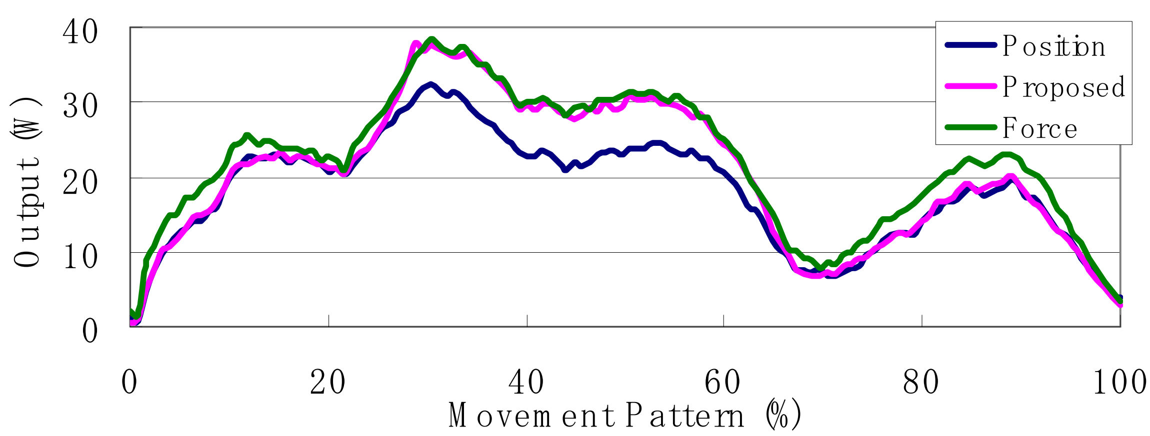
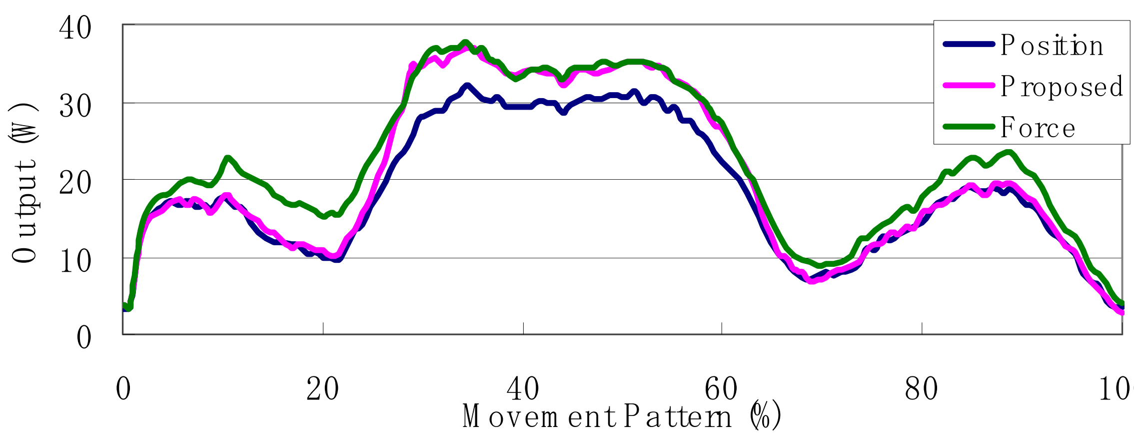


Fig. 17. Applied force.

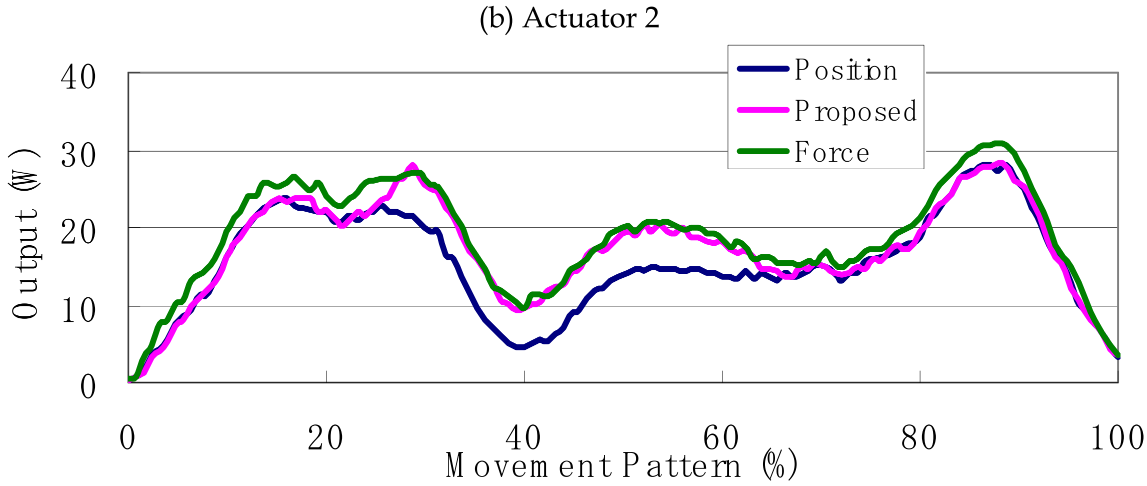
Fig. 18 shows power output of each actuator during standing assistance. Force assistance mode requires high output comparing with position mode. Total required power of the assistance system and the patient for once standing up motion is constant, therefore, we can evaluate that the load of the patient reduces in force assistance mode. Our proposed assistance mode requires high output during 25 to 65[%] movement pattern and this means our system selects force control and the load of the patient reduces during this period.
Table 3 shows the workload of our system for standing assistance. Force mode requires 147[%] workloads comparing with position mode. On the other hand, our proposed assistance mode requires only 112[%] workloads and this means the patient are required to use more own physical strength.
From these results, our proposed assistance scheme reduces the load of the patient in third phase and uses the physical strength of the patient at a whole assistance motion.



(a) Actuator 1



(b) Actuator 2



(c) Actuator 3

Fig. 18. Traction output of the assistance system.

	Position	Proposed	Force
Actuator1	68.7	77.7 (113.1%)	100.3 (146.0%)
Actuator2	69.2	76.5 (110.5%)	100.8 (145.7%)
Actuator3	57.5	65.3 (113.6%)	85.2 (148.2%)
Total	195.4	219.5 (112.3%)	286.3 (146.5%)

* Values in parentheses are the ratio comparing with the position mode.

Table 3. Workload of our system (Ws)

7. Conclusion

In this paper, we develop the novel assistance system for the standing up motion. Our system focuses on family use and our system is required to assist the elderly person using part of their remaining strength, in order not to reduce muscular strength.

In order to fulfill this condition, we propose new assistance manipulator mechanism with parallel linkages. Our developed mechanism enables the assistance system to be rigid and compact with low costs.
Furthermore, we design the novel control scheme which combines the dumping and the position control. According to the posture of the patient during standing up motion, our control system can select more appropriate control method from them. Using our assistance system, the load of the patient reduces in third phase, which applies the heaviest load during the motion generally. At the same time, our system requires the patient to use own more physical strength comparing with physical strength without the force assistance. This means our assistance system realizes both reducing the load of the patient and using a part of remaining strength of the patient in order not to reduce muscular strength.

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Population ageing has major consequences and implications in all areas of our daily life as well as other important aspects, such as economic growth, savings, investment and consumption, labour markets, pensions, property and care from one generation to another. Additionally, health and related care, family composition and life-style, housing and migration are also affected. Given the rapid increase in the aging of the population and the further increase that is expected in the coming years, an important problem that has to be faced is the corresponding increase in chronic illness, disabilities, and loss of functional independence endemic to the elderly (WHO 2008). For this reason, novel methods of rehabilitation and care management are urgently needed. This book covers many rehabilitation support systems and robots developed for upper limbs, lower limbs as well as visually impaired condition. Other than upper limbs, the lower limb research works are also discussed like motorized foot rest for electric powered wheelchair and standing assistance device.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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